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Baryon Production from Pion Fragmentation in the Quark Recombination Model

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ABSTRACT

The quark recombination model is used to analyze low p_{\perp} baryon production from pion projectiles. Experimental inclusive cross sections for $\pi^+p \rightarrow p^+X$ obtained recently at Fermilab energies show that these reactions differ from each other in their x behavior. This distinctive feature is reproduced in a self-consistent formulation of the recombination model. A novel parametrization of the joint sea quark distribution function is introduced and interpreted. A prediction for $\pi^-p \rightarrow p^+X$ is in excellent agreement with experiment. These results support the view that the quark recombination model can be used to obtain information about the pion sea.

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I. INTRODUCTION

The observed connection^{1,2} between the leading particle distribution and the projectile parton structure functions has been incorporated by Das and Hwa³ into a quantitative description of the low p_{\perp} single particle inclusive cross section by the recombination function and convolution integral ideas of the quark recombination model. The inclusive distribution $E d\sigma/d^3p$ (p_{\perp} integrated) = $H(x)$ is given by

$$H_M^{QQ}(x) = \int_0^x \frac{dx_1}{x_1} \int_0^{x-x_1} \frac{dx_2}{x_2} F_2(x_1, x_2) R_2(x_1, x_2, x) \quad (1)$$

and

$$H_B^{QQQ}(x) = \int_0^x \frac{dx_1}{x_1} \int_0^{x-x_1} \frac{dx_2}{x_2} \int_0^{x-x_1-x_2} \frac{dx_3}{x_3} F_3(x_1, x_2, x_3) R_3(x_1, x_2, x_3, x) \quad (2)$$

for the production of mesons and baryons respectively. The $F(x)$ are the joint quark distribution functions, the $R(x)$ the recombination functions and QQ distinguishes VS (valence-sea), VV or SS recombination processes while QQQ distinguishes VVV, VVS, VSS and SSS.^{4,5}

The model has been successful, mainly for the proton beam, in describing meson distributions,^{3,6} baryon distributions,^{7,8} two particle distributions⁹ and correlations with the Drell-Yan mechanism.¹⁰ In these applications the recombination model has utilized the proton parton distributions obtained from lepto-production¹¹ and in this way a description of the proton sea quark distributions has been extracted.¹² Little is known about the meson quark structure functions¹³ as they are not available from lepto-production. It has been realized recently that the quark recombination model, when used to analyze distributions from a meson beam, can provide information about the meson quark structure functions.¹⁴⁻¹⁶

Baryon distributions in the meson fragmentation region offer new and challenging features which favor the application of the quark recombination model and provide a unique opportunity to probe the pion sea. Resonance contributions to meson spectra are expected to be significant^{6,12,18,20,21} although there is no agreement as how to extract this accurately, whereas a contribution from resonances to baryon distributions is not so important.²¹ A meson fragmenting into a baryon is a VSS type recombination process which has not been studied and offers a good test of recombination model ideas since it is a simple recombination mechanism involving only one valence quark. The valence-valence correlation effects that are important in previously studied baryon final states: $p \rightarrow p, n, \Lambda$ ^{7,8} are not present; thus a clear valence quark signal and an unambiguous separation of the pion sea can be expected.

In this paper the quark recombination model is formulated for nonstrange baryon distributions in the pion fragmentation region. A distinctive feature has been observed in the x behavior of $\pi^+p \rightarrow p^\pm X$: when the experimental distributions are fitted using $E d\sigma/d^3p \propto (1-x)^n$ the result is that for $\pi^+p \rightarrow pX$ $n = 1.78 \pm 0.14$ and for $\pi^+p \rightarrow \bar{p}X$ $n = 2.95 \pm 0.25$.¹⁸ The quark recombination model in its original formulation cannot explain this discrepancy; however in the more refined formulation of the model that is presented here this anomalous behavior is accounted for by a novel parametrization that provides new information about the structure of the pion sea.

In Section II the quark recombination model is formulated for valence-sea-sea recombination in the pion fragmentation region. In Section III the results for $\pi^+p \rightarrow p^\pm X$ are presented and the parameters of the model are established. Predictions are made for $\pi^-p \rightarrow p^\pm X$. In Section IV a discussion of the results is presented.

II. QUARK RECOMBINATION MODEL FOR BARYON PRODUCTION FROM INCOMING MESONS

For the reactions $\pi^+ p \rightarrow p^\pm X$ the inclusive single particle distribution is given by

$$H_B^{VSS}(x) = \int_0^x \frac{dx_1}{x_1} \int_0^{x-x_1} \frac{dx_2}{x_2} \int_0^{x-x_1-x_2} \frac{dx_3}{x_3} F_3(x_1, x_2, x_3) R_3(x_1, x_2, x_3, x) \quad (3)$$

where the x_i are the momentum fractions of the various quarks (see Fig. 1). For the recombination function it is assumed that the recombination of more than three partons is unimportant and for the reactions considered here the VSS mechanism is assumed to dominate the possible contribution from SSS recombination. For the VSS recombination process a clear valence quark signal is expected. In the kinematic region of interest the momentum fraction of the valence quark is much larger than the momentum carried by the other quarks in the incident hadron and it is reasonable to assume that a valence quark distribution will factor from the joint-three-quark distribution. This is similar to the original idea and observation of Ochs.¹ We write

$$F_3(x_1, x_2, x_3) = F_v^\pi(x_1) \rho(x_1, x_2, x_3) F_2(x_2, x_3) \quad (4)$$

where $F_v^\pi(x_1)$ is a valence quark distribution in the incident pion, ρ is a phase space function and $F_2(x_2, x_3)$ is interpreted as the joint distribution of two quarks in the enhanced pion sea.

Following Ranft⁷ and generalizing Das and Hwa³ the three quark recombination process is flavor independent and the recombination function has the simple form

$$R_3(x_1, x_2, x_3, x) = \alpha_B \left(\frac{x_1 x_2 x_3}{x^3} \right)^N \delta \left(1 - \frac{x_1}{x} - \frac{x_2}{x} - \frac{x_3}{x} \right)$$

where the delta function conserves momentum and α_B is a constant which might distinguish mass or spin states but is assumed to be the same for the reactions being considered. Most applications of the quark recombination model to date have used the simple form of R_3 with $N = 1$;^{7,8} Hwa²² however has recently derived the exponent in R_3 to be $N = 3/2$. We have found that the resulting baryon distributions hardly differ for $N = 1$ or $3/2$ and the results presented in Section III have been obtained with $N = 3/2$. The phase space function is assumed to be flavor independent and given by

$$\rho(x_1, x_2, x_3) = \beta (1 - x_1 - x_2 - x_3)^k$$

where β is a constant. The exponent k is a variable parameter which is obtained by fitting to the data. The inclusion of this parameter has been found necessary for baryon distributions from the proton beam also.^{7,8}

The joint sea quark distribution function $F_2(x_2, x_3)$ is the new feature of the quark recombination model that is unique to the VSS mechanism and should provide new insight into the structure of the pion sea. To proceed it is necessary to make some assumptions about the form of this distribution function. The difference in the x behavior for the reactions $\pi^+ p \rightarrow pX$ and $\pi^+ p \rightarrow \bar{p}X$ is unexpected in the simple quark recombination model. Since the flavor independence of R_3 and ρ is basic to the model we are led to look for an explanation for this phenomenon in the structure of the pion sea. Considering the quark flow lines appropriate to the two reactions (see Fig. 1) one observes that the only difference is that for $\pi^+ p \rightarrow \bar{p}X$ the sea quarks (or antiquarks) are flavor identical while for $\pi^+ p \rightarrow pX$ the sea quarks are

flavor distinguishable. This observation has motivated us to assume that for $\pi^+p \rightarrow \bar{p}X$, where the sea quarks are identical, the joint quark distribution function will factor into two independent single quark distributions whereas for $\pi^+p \rightarrow pX$ it is possible for the two sea quarks to display a more correlated behavior. These assumptions are supported by the results presented in the next section. Before we write down the explicit parametrizations used for the joint sea quark distributions it is necessary to review pion single quark distributions.

There is obviously no experimental information on $vW_2^{e\pi}(x)$ and so the pion quark distributions cannot be determined from leptonproduction as it has been possible for the nucleon.¹¹ Recently however it has been shown that empirical parametrizations of the pion quark structure functions can be extracted from hadron hadron scattering. Various analyses of meson production using the quark recombination model¹⁴⁻¹⁶ and a recent analysis of muon pair production²³ give for the valence quark distribution $F_V^\pi(x) \sim (1-x)$. In a recent quark recombination model analysis by Biswas and collaborators²⁴ the pion sea quark distribution was found to behave like $F_S^\pi(x) \sim (1-x)^5$. These results for the valence and sea quark distributions in the pion are in agreement with the Dimensional Counting Rule¹⁷ expectations (see Fig. 2).

For the calculations presented in this paper we have taken for the pion valence quark distribution

$$F_V^\pi(x) \sim (1-x) \quad .$$

For the case of a factorizable joint sea quark distribution we use

$$F_2^\pi(x_2, x_3) = F_S^\pi(x_2)F_S^\pi(x_3) \sim (1-x_2)^5(1-x_3)^5 \quad . \quad (5)$$

The second form for F_2 (i.e. the nonfactorizable form) is obtained by using the Dimensional Counting Rule to directly predict the description of two sea quarks in the pion (see Fig. 2c) giving

$$F_2^\pi(x_2, x_3) \sim [1 - (x_2 + x_3)]^7 \quad . \quad (6)$$

Finally, a symmetric valence quark model is adopted:

$$F_u^{\pi^+}(x) = F_d^{\pi^+}(x) = F_v^\pi(x) \quad (7)$$

and an SU(3) symmetric sea is assumed:

$$F_u^{\pi^+}(x) = F_d^{\pi^+}(x) = F_{u,\text{sea}}^{\pi^+}(x) = F_{d,\text{sea}}^{\pi^+}(x) = F_s^\pi(x) \quad . \quad (8)$$

The π^- distributions are obtained by charge conjugation.

III. RESULTS

According to the formalism developed in the previous section we have two possible invariant cross sections for the valence-sea-sea recombination into a baryon in the pion fragmentation region:

$$H_1^{VSS}(x) = \int_0^x \frac{dx_1}{x_1} \int_0^{x-x_1} \frac{dx_2}{x_2} \int_0^{x-x_1-x_2} \frac{dx_3}{x_3} F_v^\pi(x_1)(1-x_1-x_2-x_3)^k \times (1-x_2)^5 (1-x_3)^5 \quad (9)$$

or

$$H_2^{VSS}(x) = \int_0^x \frac{dx_1}{x_1} \int_0^{x-x_1} \frac{dx_2}{x_2} \int_0^{x-x_1-x_2} \frac{dx_3}{x_3} F_v^\pi(x_1)(1-x_1-x_2-x_3)^k \times (1-x_2-x_3)^7 \quad (10)$$

Initially for the analysis we have neglected the assumptions leading to the different forms of F_2 and have tested both possible cross sections, i.e. equations (9) and (10), against experimental data.

In Figure 3 the invariant inclusive cross section predicted by equation (9) (i.e. factorized form of F_2) is compared to the experimental data for $\pi^+p \rightarrow p^\pm X$ at $p_{lab} = 100$ GeV/c. The calculation is normalized to the data at $x = 0.3$ and various values of the parameter k were tested. An adequate fit is obtained with $k = 2.5 \pm 0.5$. In Figure 4 the invariant inclusive cross section predicted by equation (10) (i.e. nonfactorized form of F_2) is compared to the same data for various values of the parameter k . A good description of the data is again possible, for some value of k .

The arbitrary values of the parameter k is an undesirable feature of this model, especially since the phase space factor ρ was introduced only as a kinematic constraint and should not be dependent on flavor. With this as a motivation, a remarkable feature of the results is observed when $k = 2.5$: a good description of $\pi^+p \rightarrow \bar{p}X$ is obtained using equation (9) and a good description of $\pi^+p \rightarrow pX$ is obtained using equation (10). This is precisely the result expected according to the assumption that the form of F_2 depends on the flavor identities of the sea quarks, as described in the previous section. By adopting this phenomenological ansatz, i.e. $k = 2.5$, the characteristic x behavior distinguishing the experimental distributions is constrained within the parametrization of the pion joint sea quark distribution function.

A test of the model is provided by the pair of reactions $\pi^-p \rightarrow pX$ and $\pi^-p \rightarrow \bar{p}X$. The similarity of these reactions to the π^+ initiated reactions is shown in Fig. 1. Our model predicts that these reactions can be described with $k = 2.5$ and using the factored form for F_2 (equation (5)) for $\pi^-p \rightarrow pX$ and using the correlated form for F_2 (equation (6)) for $\pi^-p \rightarrow \bar{p}X$. Experimental data are available for these reactions.¹⁸ The characteristic discrepancy in the x behavior of the two reactions is observed: it is found that for $\pi^-p \rightarrow pX$ $n = 2.58 \pm 0.20$ and for $\pi^-p \rightarrow \bar{p}X$ $n = 2.13 \pm 0.05$. A comparison of our prediction with the experimental data for $\pi^-p \rightarrow p^\pm X$ at 100 GeV/c¹⁹ is shown in Figure 5. The results are in excellent agreement with experiment. For comparison and completeness, we have also shown in Figure 5 the corresponding results for the reactions $\pi^+p \rightarrow p^\pm X$.

The self-consistency of the description of the π^+ initiated reactions and the success of the prediction for the π^- initiated reactions together give strong support to the assumption that the anomalous x behavior of these reactions can be attributed to structure in the pion sea.

IV. DISCUSSION

We have shown that the quark recombination model can be used to describe the distinctive x behavior of the invariant inclusive distributions for $\pi^+p \rightarrow p^\pm X$ and $\pi^-p \rightarrow p^\pm X$ when two parametrizations of the pion sea are introduced. A possible simple interpretation for the results shown in Figure 5 is suggested when the parametrization of $F_2(x_2, x_3)$ by equation (5) is interpreted as indicating independent events and it is observed that the sea quarks (or antiquarks) needed in $\pi^+p \rightarrow \bar{p}X$ and $\pi^-p \rightarrow pX$ are of the same flavor, whereas the parametrization of $F_2(x_2, x_3)$ by equation (6) suggests a more correlated sea quark-sea quark distribution which is appropriate when the sea quarks (or antiquarks) have different flavors as in $\pi^+p \rightarrow pX$ and $\pi^-p \rightarrow \bar{p}X$ (see Fig. 1). An understanding of the somewhat arbitrary phase space function would be necessary before this speculation could be given a theoretical foundation; nonetheless, the result is remarkable in view of the simplicity of the formulation and the excellent description of the experimental distributions. It is clear that the unexpected x behavior of these distributions is the result of some underlying structure in the pion sea.

The low p_\perp baryon production reactions that have been analyzed here cannot be described by the simple quark recombination model nor by the other low p_\perp quark models. The quark fragmentation model²⁵ focuses on the final state and cannot be used until baryon production fragmentation functions are available. The fragmentation counting rule¹⁷ does not give an adequate description of the cross sections for these reactions although the quark exchange or annihilation interaction is clearly preferred to gluon exchange.¹⁸ An important question that remains unsolved involves the determination of the magnitude. The problem of predicting the magnitude of the invariant cross sections, and in particular the problem of incorporating the p_\perp dependence, is a well-known difficulty[†] of the quark

[†] Compare for example the approaches of Refs. 2, 3, 6, 7, 15. Many of the problems associated with normalization can be avoided if enough data is available to consider ratios of cross sections (e.g. see Ref. 12).

recombination model. It would be very instructive to extend the model presented here to strange baryon production and to kaon beams. With invariant cross sections for such reactions it would be possible to probe the pion strange sea and to obtain information about the K meson quark structure functions. This would be an important test of the VSS recombination model and of the parametrization presented here. Work along these lines is in progress.

In conclusion, using a pion valence quark distribution like $F_V^\pi(x) \sim (1-x)$ in a self-consistent quark recombination type model we have successfully described the distinctive x behavior of the low p_\perp reactions $\pi^+p \rightarrow p^\pm X$ and $\pi^-p \rightarrow p^\pm X$. It is argued that these reactions are particularly good for testing recombination model ideas. The results are very sensitive to the form of the joint-sea-quark distribution, and an underlying structure in the pion sea is revealed. A deeper understanding of the joint quark distribution function in the recombination model is needed to give a theoretical foundation to the phenomenological results presented here. This study shows that the recombination model can be effective in extracting information about the pion quark sea.

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FIGURE CAPTIONS

- Fig. 1: Schematic diagram for the low p_{\perp} baryon production reactions $\pi^+p \rightarrow p^{\pm}X$ and $\pi^-p \rightarrow p^{\pm}X$ in the VSS quark recombination model.
- Fig. 2: Diagrams used to count the spectator quarks (n_s) to obtain the pion quark distributions for a) a valence quark, b) a sea quark, c) two sea quarks. The dimensional counting rule predicts $F^{\pi}(x) \sim (1-x)^{2n_s-1}$ (Ref. 17).
- Fig. 3: Invariant inclusive cross sections for $\pi^+p \rightarrow p^{\pm}X$. The solid lines are the results obtained using equation (9) and various values of the parameter k . The experimental data are at $p_{lab} = 100$ GeV/c and $p_{\perp} = 0.3$ GeV/c taken from Ref. 18.
- Fig. 4: Invariant inclusive cross sections for $\pi^-p \rightarrow p^{\pm}X$. The solid lines are the predictions obtained using equation (10) and various values of k . The experimental data are at $p_{lab} = 100$ GeV/c and $p_{\perp} = 0.3$ GeV/c taken from Ref. 18.
- Fig. 5: Invariant inclusive cross sections for $\pi^+p \rightarrow p^{\pm}X$ and $\pi^-p \rightarrow p^{\pm}X$. The solid lines are the predictions constrained by $k = 2.5$ and grouped according to the parametrization of the joint sea quark distribution as described in the text. The data are from Refs. 18 and 19 at $p_{lab} = 100$ GeV/c and $p_{\perp} = 0.3$ GeV/c.

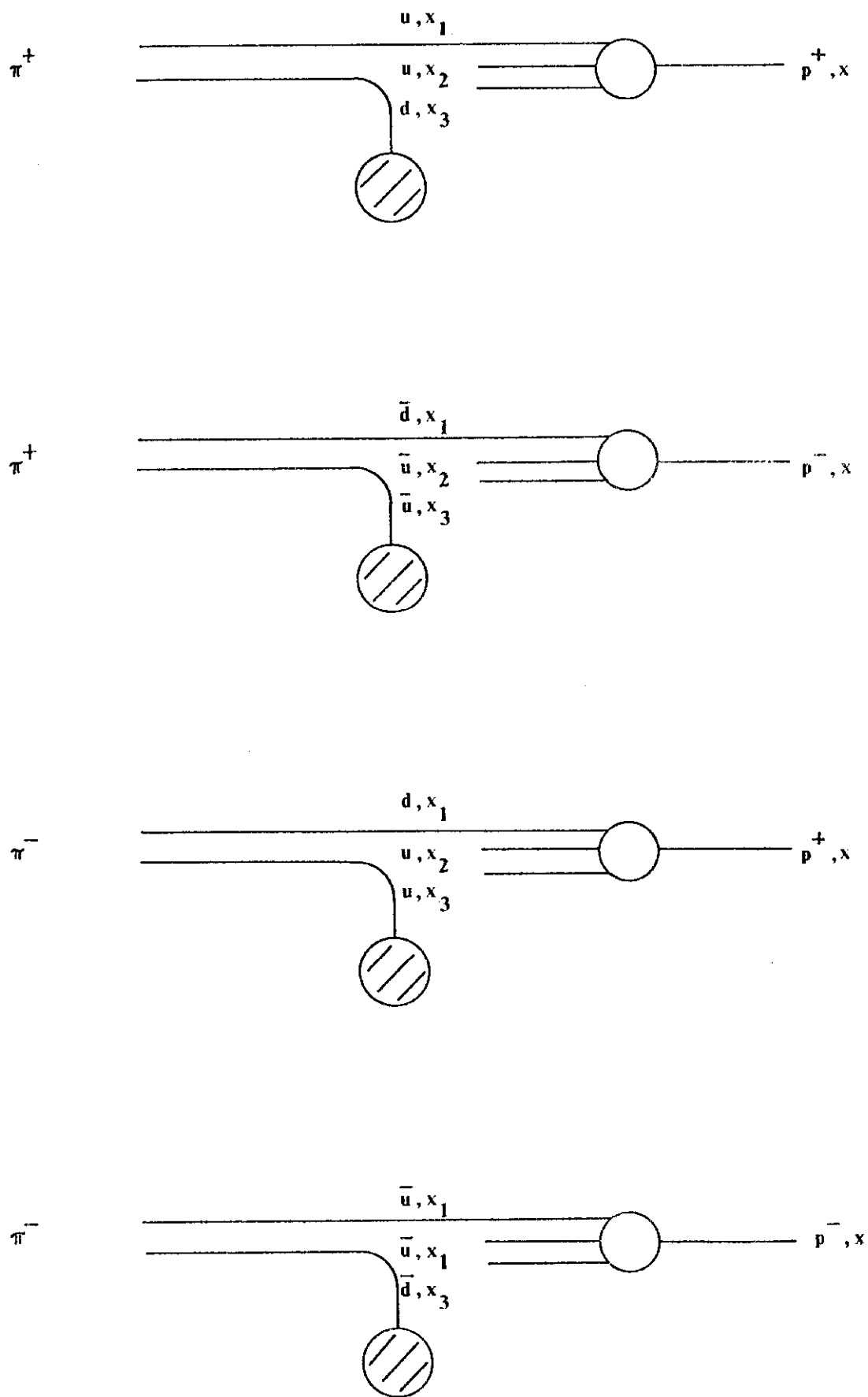


Figure 1

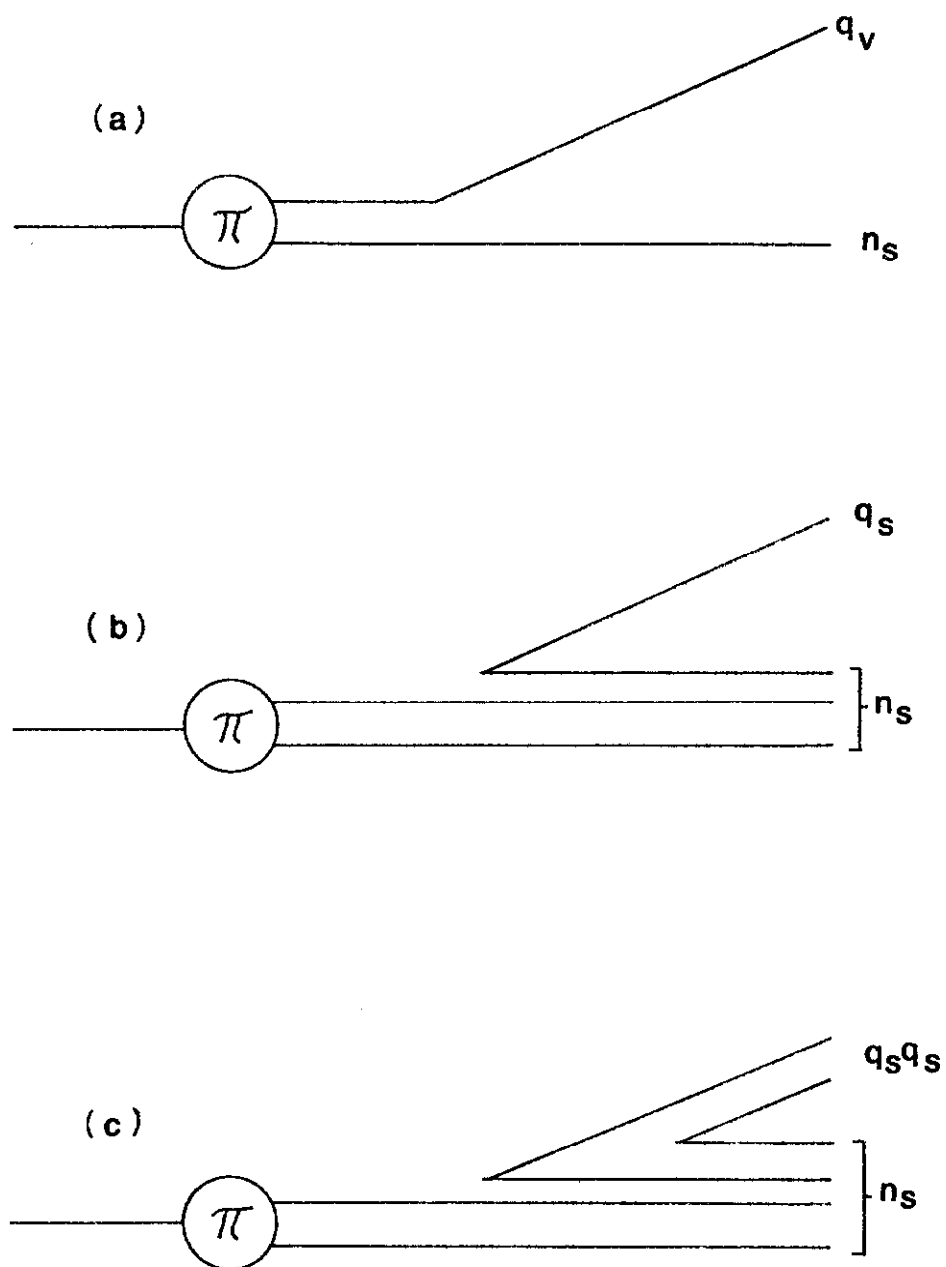


Figure 2

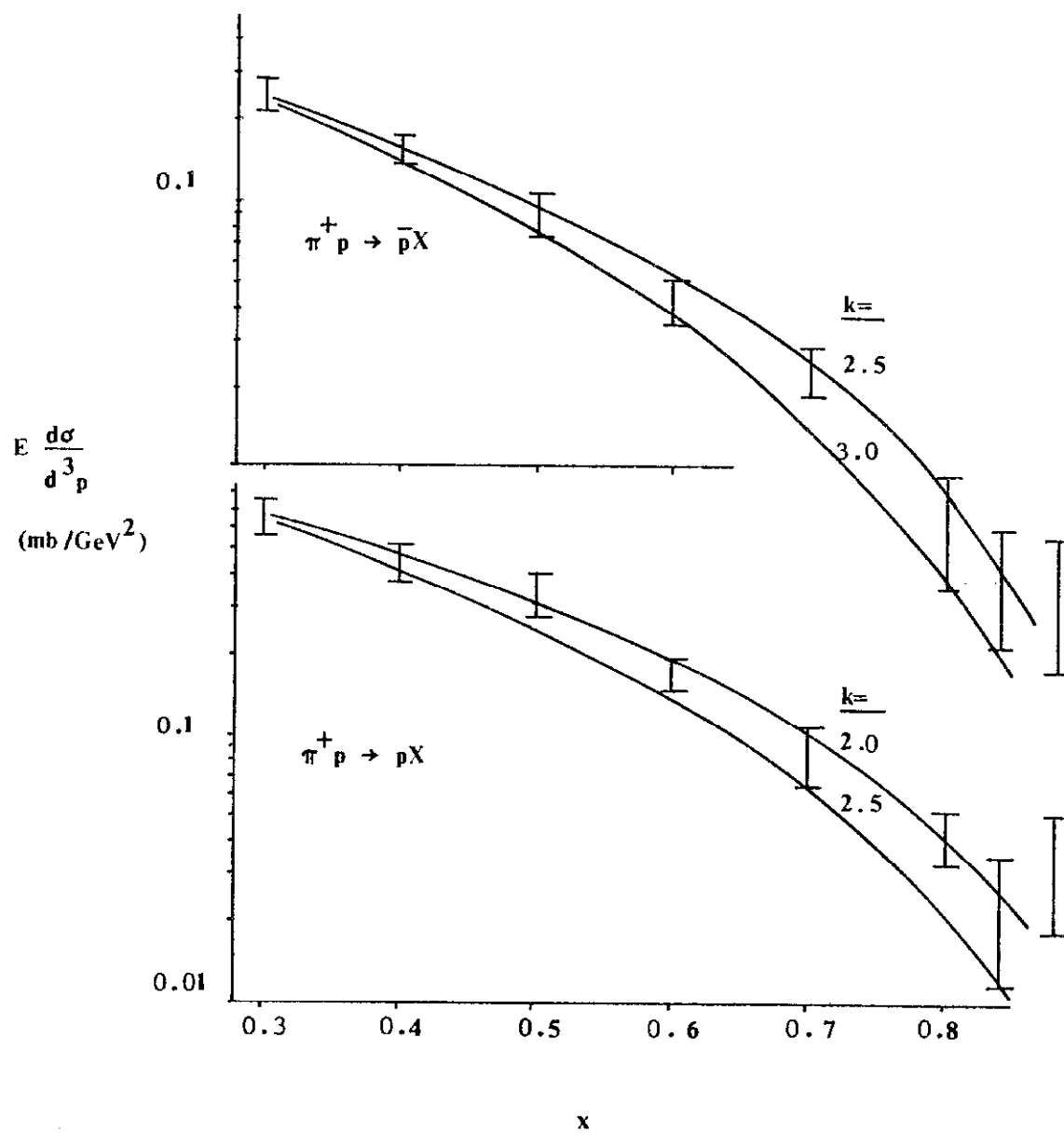


Figure 3

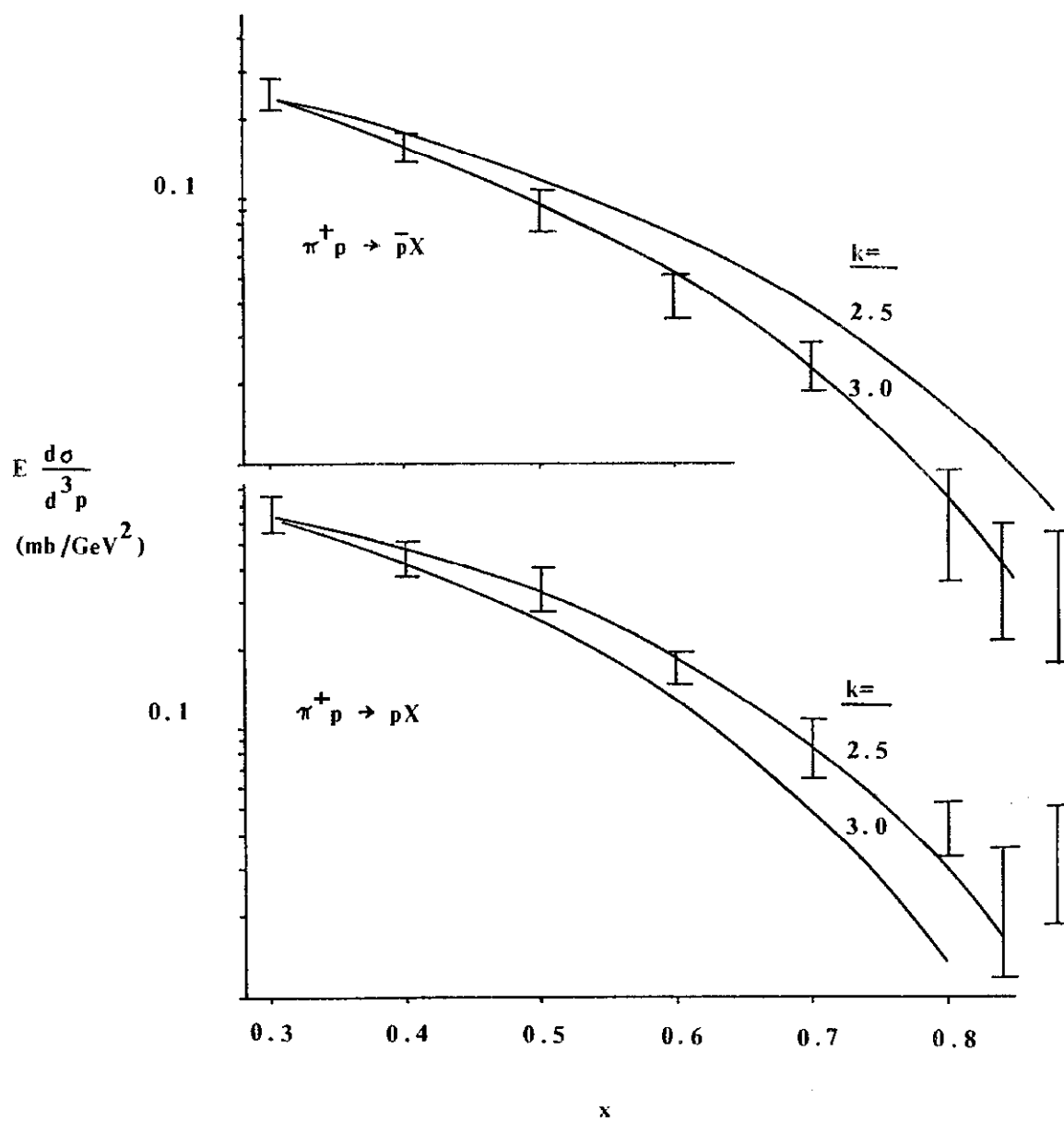


Figure 4

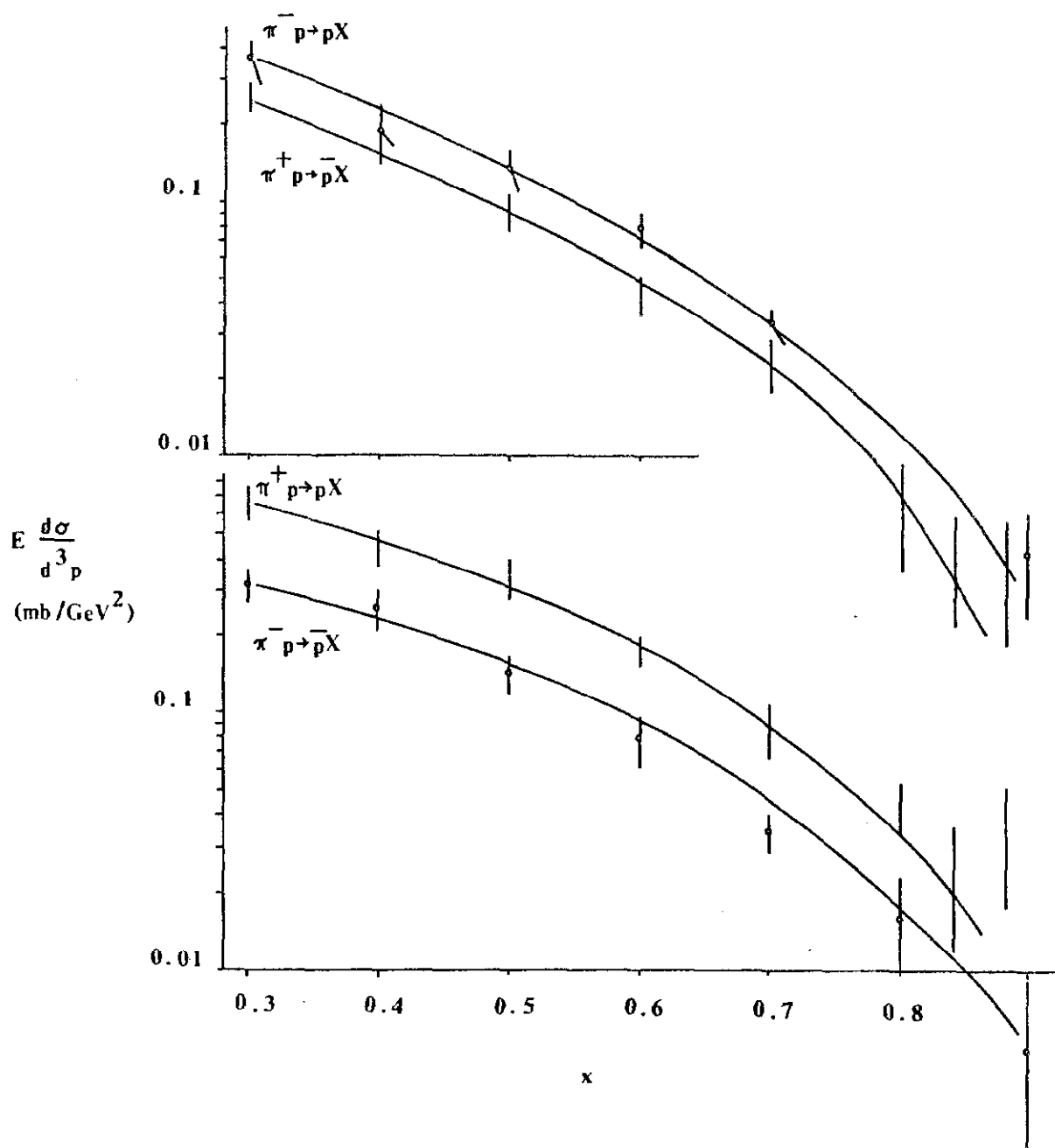


Figure 5